

Development
of
ULTRASONIC WELDING EQUIPMENT
for
REFRACTORY METALS

by

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47853

AEROPROJECTS INCORPORATED

WEST CHESTER, PENNSYLVANIA

Contract: AF 33(600)-43026

ASD Project No. 7-888

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WARNING

The requirements established during Phase I for a heavy-duty ultrasonic welding system are being analyzed, and associated development problems are being resolved. High-power ceramic transducer assemblies, power-force programming elements, and switching devices for a motor-alternator power source are being assembled and experimentally evaluated. Current information on refractory metal developments affecting the ultrasonic weldability of such material, as well as data on candidate welding tip materials, is being accumulated and studied.

FABRICATION BRANCH
MANUFACTURING TECHNOLOGY LABORATORY

AFSC Aeronautical Systems Division
United States Air Force
Wright-Patterson Air Force Base, Ohio

ABSTRACT-SUMMARY
Interim Technical Progress Report

ASD Interim Report 7-888(III)
May, 1962

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The requirements established during Phase I for a heavy-duty ultrasonic welding system are being analyzed, and associated development problems are being resolved. High-power ceramic-transducer assemblies, power-force programming elements, and switching devices for a motor-alternator power source are being assembled and experimentally evaluated. Current information on refractory metal developments affecting the ultrasonic weldability of such material, as well as data on candidate welding-tip materials, is being accumulated and studied.

General
Information, derived from the current literature and other sources, is presented for: Cb(D-31), Mo-0.5Ti, Rene 41, and tungsten. Composition and physical properties are summarized for five candidate welding tip materials: Astroloy, Udimet 700, Udimet 500, NIMONIC 115, and Microtung. These materials, except for Microtung, are all nickel alloys of similar composition. *Rene*

The design of a tension-shell transducer unit with increased power-handling capacity was evolved, and an acoustic absorber for measuring the transducer conversion efficiency calorimetrically was assembled and utilized.

An aluminum-bronze coupler element was fabricated, installed in a 2-kilowatt ultrasonic welder, and successfully operated to the limited power capacity of this welder.

A portion of the time-base circuitry for the power-force programming system was evaluated. The results met the tentative design requirements of a 0.002-second maximum time delay.

The performance of a 7.5-kilowatt motor-alternator and the stability of the critical frequency-controlling elements demonstrated the practicality of powering ultrasonic spot-welding equipment with such a rotating machine power source. Solid-state switching devices with a response time of 8 to 12 microseconds will probably be used if the projected 25-kilowatt ultrasonic welding machine is powered by a motor alternator.

Design of the primary welding machine structure was initiated.

FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF 33(600)-43026 from February 1 through April 30, 1962. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Aeroprojects Incorporated of West Chester, Pennsylvania, was initiated under ASD Manufacturing Technology Project 7-888, "Development of Ultrasonic Welding Equipment for Refractory Metals". It was administered under the direction of Fred Miller of the Fabrication Branch (ASRCTF), Manufacturing Technology Laboratory, AFSC Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

This project is under the direction of J. Byron Jones, with Nicholas Maropis serving as Project Engineer. Others associated with this program are Carmine F. DePrisco, Chief Electronics Engineer; John G. Thomas, Metallurgist; Janet Devine, Physicist; Jozef Kozlarski, Ultrasonic Welding Laboratory Director; W. C. Elmore, Consultant; and Roberta McCutchen, Senior Technical Writer. This document has been given the Aeroprojects internal report number of RR-62-30. This is an interim report; the information reported herein is preliminary and subject to further analysis and modification as the work progresses.

The methods used to demonstrate a process or technique on a laboratory scale are inadequate for use in production operations. The objective of the Air Force Manufacturing Methods Program is to develop on a timely basis, manufacturing process, techniques and equipment for use in economical production of USAF materials and components. This program encompasses the following technical areas:

Rolled Sheet	Powder
Forgings	Component Fabrication
Extrusions	Joining
Castings	Forming
Fiber	Material Removal
Fuels and Lubricants	Solid State Devices
Ceramics and Graphites	Passive Devices
Nonmetallic Structural Materials	Thermionic Devices

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated. Direct any reply concerning the above matter to the attention of Mr. W. W. Dismuke, ASRKRA.

PUBLICATION REVIEW

Approved by:



J. Byron Jones

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DEVELOPMENT
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Phase II

INTRODUCTION

Since ultrasonic welding was first demonstrated as a practical method for joining thin gages of aluminum and other common metals and alloys, the equipment capability has been continuously extended to joining materials of increasing thickness as well as newer metals and alloys that are difficult or impossible to weld by other techniques. The aerospace need for high-temperature, corrosion-resistant, refractory metals and alloys has increased the need for ultrasonic welding machines of greater capability than are now available.

The objective of this program is to design, assemble, and evaluate heavy-duty ultrasonic spot- and seam-welding equipment for joining refractory materials and superalloys in thicknesses up to 0.10 inch and to develop necessary techniques for producing reliable welds in these materials. The accomplishment of this objective is divided into three phases: Phase I is concerned with establishing feasibility, defining problem areas, and delineating appropriate solutions thereto; Phase II embraces the development of the required equipment and techniques; and, under Phase III, the performance characteristics of the ultrasonic welding equipment will be demonstrated.

Under Phase I, completed prior to the current reporting period (1), the feasibility of producing ultrasonic welds in both monometallic and bimetallic combinations of Cb(D-31), Mo-0.5Ti, Inconel X-750, PH15-7Mo stainless steel, René 41, and tungsten was demonstrated. By extrapolating the weldable gage capability of 4-kilowatt and 8-kilowatt ultrasonic spot-type welders, and utilizing a previously developed first-approximation criterion for the energy required to weld materials of various hardnesses and thicknesses, the electrical power input to the transducer necessary to join the above materials in gages up to 0.10 inch was estimated as approximately 25 kilowatts (2).

Also under Phase I, the problems involved in the production of heavy-duty ultrasonic welding equipment were delineated, a systematic approach to solving problems was outlined, and design parameters for the requisite heavy-duty spot-welding equipment were defined. The basic concepts involved in such machines were investigated. Spot-type welders for high-power operation were studied in considerable detail; both theoretical and experimental information were evolved to provide preliminary design requirements for this type of machine.

A survey of the "state of the technology" of transducer materials and coupler materials, supplemented by laboratory investigations, indicated that the transducer-coupling system for the heavy-duty equipment should utilize lead-zirconate-titanate ceramic transducers and aluminum-bronze or beryllium-copper coupling members. The requisite vibratory power can be delivered to the weld zone by means of an opposition-drive transducer-coupling system. Astroloy, a nickel-base alloy made by General Electric Company, was tentatively selected to meet the welding tip material requirements.

The transducer-coupling systems will be driven by either a motor alternator or an electronic generator providing about 25 kilowatts of electrical power. If the motor alternator is selected, solid-state elements may be used to meet the switching requirements.

The work initiated under Phase II has the following objectives:

1. Develop the necessary methods, techniques and equipment to ultrasonically join the selected materials.
2. Design and construct ultrasonic joining unit(s) in accordance with the approach outlined in Phase I.
3. Develop methods and techniques to demonstrate the capability of the equipment developed under Phase II to join the selected materials.

This report describes the work accomplished during the first three months of this phase -- February through April 1962. Emphasis was placed on: investigations related to the properties of the weldment materials, as well as further consideration of welding machine tip materials; the development of the primary equipment elements required in the 25-kilowatt ultrasonic spot-type welding equipment. The third item above, equipment capability studies, will be initiated when the equipment has been assembled.

I. MATERIAL INVESTIGATIONS

"THE OBJECT OF PHASE II IS TO DEVELOP THE NECESSARY METHODS, TECHNIQUES, AND EQUIPMENT TO ULTRASONICALLY JOIN THE SELECTED MATERIALS."

While Phase II primarily involves equipment development, the projected 25-kilowatt ultrasonic welding machine will be evaluated by welding the refractory metals, PH15-7Mo stainless steel,* Cb(D-31), Mo-0.5Ti, René 41, and tungsten, in thicknesses up to 0.10 inch. Since the characteristics of these refractory metals change as their quality is improved, the weldability of the material is affected. Accordingly, the current literature on refractory metal developments is being reviewed, and liaison is being maintained with both the Defense Metals Information Center (DMIC), Columbus, Ohio, and the manufacturers of these materials to keep abreast of material changes. That continuous progress is being made is evident from the information published in the weekly issues of DMIC's "Review of Recent Developments."

If this ultrasonic welding unit is to operate with maximum effectiveness, sonotrode tips for the final welding machine must be tough, resistant to wear, and retain satisfactory physical properties at elevated temperatures. Accordingly, information on candidate tip materials is being acquired and reviewed.

WELDMENT MATERIALS

A visit to DMIC on March 7-8 (3) and attendance at the 1962 Refractory Metals Symposium on April 12-13 (4) provided sources of information and data on the six prescribed materials which are being used in estimating the response of the materials to ultrasonic welding and in providing the background for interpreting welding results.

The alloys, Inconel-750, René 41 (15), and PH15-7Mo, are now relatively accepted structural materials, and methods for their fabrication have been standardized to insure a uniform product. Formability and methods of joining have been studied. For example, solution-annealed René 41 is susceptible to grain-boundary carbide precipitation in the range of 1400 to 1500°F. The embrittling effect of the precipitation precludes fabricating in this temperature region.(5) Brazing at these temperatures, or fusion welding where a heat-affected zone is produced, results in similar embrittlement. Ultrasonic welding should produce no such effect.(6)

* Substituted for AM-355 stainless steel in Phase I studies.

Tungsten, Cb(D-31), and Mo-0.5Ti are the continuing subject of extensive investigation (7-14). Since fabricability procedures are constantly being modified, a "standard" commercial product has not yet evolved. Tungsten, Mo-0.5Ti, and Cb(D-31) suffer recrystallization embrittlement and must be worked below recrystallization temperatures. The resulting grain structure of the rolled sheet is fibrous and the properties are sensitive to the rolling direction unless cross-rolling is utilized (3). The ductile-brittle behavior of the body-centered-cubic lattice, as well as embrittlement sensitivity from small interstitial contaminant levels, contribute to difficulties in achieving sound joints by conventional welding methods. Current research is providing information which is being used to improve fabrication techniques and to produce alloys of superior compositions. For example, tungsten alloyed with rhenium has increased ductility, tensile strength, and oxidation resistance (5, 12). Ductility of unalloyed tungsten wire has been improved by electroetching the surface of the wire (13). Boeing has reported improving the ductility of Mo-0.5Ti below 1000°F for forming purposes. Battelle indicates that heating Mo-0.5Ti sheet in the range of 300 to 500°F permits use of almost "zero" bend radius. Oxygen and hydrogen should be below 20 ppm for good ductility (9). According to the producer (7), the erratic behavior of the Cb(D-31) alloy can be attributed to the unstable cold-rolled and stress-relieved condition. Improvement is expected after new equipment to permit hot reduction becomes available.

Quantities of the candidate weldment materials have been ordered to supplement existing stocks on hand and to provide sufficient material for the welding studies.

TIP MATERIALS

The welding studies carried out during Phase I of this program indicated that welding tips of Astroloy* are probably capable of adequate performance with the weldment materials of interest. Astroloy is an experimental alloy; its mechanical properties and metallurgical processing are not well established and vary from one lot to another. Investigation of welding tips fabricated from this material in cast and wrought form, initiated during Phase I (16), has been continued.

Although a number of sound tips were machined from the vacuum-melted and cast stock, some of the tips failed prematurely. Radiographic examination of a cast bar revealed centerline shrinkage cavities (Figure 1), and metallographic inspection indicated that the poor performance of the tips probably resulted from macrocracks in the damaged tip contact area, which followed these shrinkage cavities (Figure 2A). Closer examination also disclosed a system of transdendritic microcracks (Figure 2B). Although it is difficult to determine the origin of these microcracks, they may be extensions of the macrocracks. In addition, prematurely failed tips fabricated from the wrought material displayed intergranular cracks (16).

* Product of General Electric Company.



Figure 1: X-RAY OF CAST-BAR ASTROLOY
(Note shrinkage cavities)

Figure 2: PHOTOMICROGRAPH OF A CAST-BAR ASTROLOY
TIP AFTER PREMATURE FAILURE

(HNO_3 -HF- H_2O Etchant)

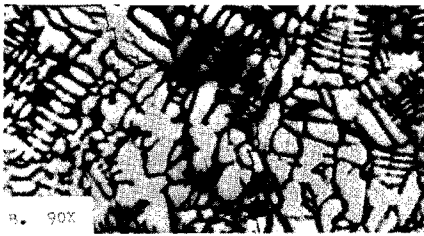


Figure 4: HOT-ROLLED ASTROLOY IN "AS FABRICATED"
CONDITION

(HNO_3 -HF- H_2O Etchant)

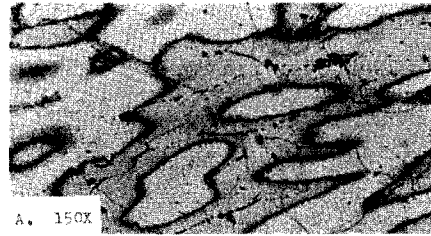


Figure 3: EXTRUDED ASTROLOY IN "AS FABRICATED"
CONDITION

(HNO_3 -HF- H_2O Etchant)

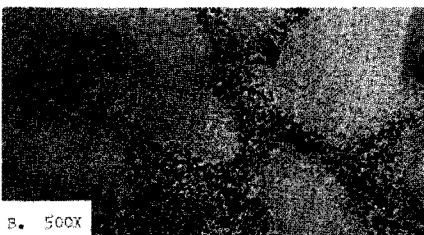
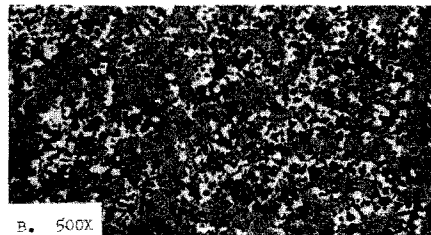
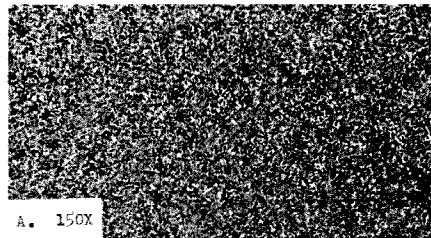


Figure 5: ROLLED-BAR UDIMET 700 STRESS-RELIEVED
AT 1975°F FOR 3 HOURS, AND AIR COOLED

(HNO_3 -HF- H_2O Etchant)



(Note: Reduced to approximately one-fourth for reproduction)

Discussions were held with a representative (17) of the General Electric Company (Jet Propulsion Division, Evendale, Ohio), who stated that General Electric is not presently working with Astroloy, and that a similar nickel-base alloy, Udimet 700,* is now being used for high-temperature jet engine applications. This material is similar to Astroloy in composition and mechanical properties, is more readily available in wrought forms, and the heat-treatment procedures have been standardized (18-19).

In Tables 1 and 2, the composition and properties of Astroloy and Udimet 700 are summarized. Also included in the tables are Udimet 500, a less heat-resistant alloy, and Microtung,** which has a somewhat different chemical composition. Discussions with representatives of DMIC elicited preliminary information concerning NIMONIC 115***, which is reportedly similar in chemical composition and properties to Astroloy and Udimet 700.

Hot-rolled and extruded bars of Astroloy in the "as fabricated" condition and hot-rolled bars of Udimet 700 in the stress-relieved condition were procured. Prior to tip fabrication, the microstructure of these materials was examined.

The extruded Astroloy (Figure 3) exhibited a dendritic structure with evidence of coring and heavy interdendritic segregation; this material has been tentatively eliminated from further consideration at this time. The hot-rolled Astroloy (Figure 4) exhibits a somewhat more uniform grain structure which retains residual dendritic segregation. The grain structure of the Udimet 700 (Figure 5) is much finer and more uniform, but its performance as a welding tip material must await evaluation in welding the materials of interest.

Two welding tips of hot-rolled Astroloy and two of Udimet 700 are being prepared and will be evaluated by welding certain of the refractory metals and alloys.

* Product of Special Metals, Inc., Utica, New York.

** Product of Westinghouse Electric Corporation.

*** Manufactured by Henry Wiggins, Ltd., Birmingham, England.

Table 1

CANDIDATE TIP MATERIALS: SOURCE AND COMPOSITION

Material	Source	Chemical Composition											
		Ni	Co	Cr	Mo	Al	Ti	C (percent)	Fe	Mn	Si	B	Other
Astroloy	Wyman-Gordon Co.	56.8	15	15	5.25	4.40	3.5	0.06	0.02*	--	--	0.03	--
Nicrotung	Westinghouse	Bal	10	12	--	4.00	4.0	0.10*	--	--	--	0.05	8.00 W 0.02 Zr
Udimet 500	Special Metals, Inc.	Bal	13	15	3.00	2.50	2.5	0.15*	4.00*	0.75*	0.75*	0.01	--
Udimet 700	Special Metals, Inc.	Bal	17 20	13 17	4.50- 5.75	3.75- 4.75	3.0 4.0	0.15*	1.00*	--	--	0.10	--

* Maximum

Table 2

CANDIDATE TIP MATERIALS: MECHANICAL PROPERTIES
IN FULLY HEAT-TREATED CONDITION

Material and Heat Treatment	Elevated Temperature Characteristics			Elongation in 2 Inches (percent)	Reduction of Area (percent)	Stress Rupture
	Tempera- ture (°F)	Tensile Strength (psi)	Yield Strength (psi)			
Astroloy (A)	Room	190,000	138,000	12	13	
	1400	150,000	122,000	15	16	23 hr at 85,000 psi (1400°F)
Microtung	Room	130,000		5		
	1600	88,000		4		
	1800	66,000		6		
Udimet 500 (B)	Room	175,000	110,000	15	15	100 hr at 73,000 psi (1350°F)
	1200	175,000	110,000	17	17	100 hr at 44,000 psi (1500°F)
	1600	95,000	70,000	23	23	100 hr at 30,500 psi (1600°F)
Udimet 700 (C)	Room	204,000	140,000	17	20	
	1400	150,000	120,000	33	40	48 hr at 85,000 psi (1400°F)
	1800	52,000	44,000	28	28	48 hr at 20,000 psi (1800°F)

Heat Treatments

A. 1975°F, 4 hours, air cool (rapid)
1550°F, 4 hours, air cool
1400°F, 16 hours, air cool

B. Not Specified

C. 2150°F, 4 hours, air cool
1975°F, 4 hours, air cool
1550°F, 24 hours, air cool
1400°F, 16 hours, air cool

II. EQUIPMENT DEVELOPMENT

"THE CONTRACTOR SHALL DESIGN AND CONSTRUCT AN ULTRASONIC JOINING UNIT IN ACCORDANCE WITH THE APPROACH OUTLINED IN PHASE I."

Problems associated with critical components of the 25-kilowatt ultrasonic welding machine are being resolved. Specifics of the work done and progress made during this report period are described below.

TRANSDUCER

TRANSDUCER DESIGN

An electromechanical conversion efficiency as high as 92 percent is theoretically attainable (20) with PZT-4 lead zirconate titanate ceramic transducer assemblies, whereas laminated magnetostrictive nickel transducers appear incapable of converting more than about 35 percent of high-frequency input electrical energy into vibratory energy (21-29). It was demonstrated experimentally in Phase I of this program (30) that the conversion efficiency of these ceramic materials is indeed higher than that of nickel. Inadequacies of the preliminary ceramic transducer assembly designs (31) and of the vibratory energy absorber (31) for measuring the output of these devices precluded accurate efficiency determinations. It was estimated, however, that ceramic transducer assemblies operating at 60-80 percent conversion efficiency could be developed during Phase II of this program.

In studies oriented to the development of ceramic washer-type transducer assemblies with an electrical power-handling capacity of 6 to 8 kilowatts, an axial tension bolt-type unit was selected as a feasible design (30-31) for applying the essential static compression load. In this design, the ratio of the ceramic washer outside diameter to its inside diameter (which we considered as an area ratio) is a controlling design parameter. This is due to the necessity for maintaining reasonable outside dimensions and roughly equivalent static and dynamic stresses (see below) in the bolt and in the compression members. These conditions, in turn, lead to increases in the height of the ceramic washer stack. Increasing the thickness of a ceramic washer may cause the magnitude of the driving voltage to exceed acceptable limits, and, alternately, adding more washers and their spacers aggravates heat dissipation difficulties.

This detail study also embraced the tension-shell type transducer design (30-31), which largely obviates the area ratio limitations but introduces other problems such as shell resonance.

Miller's (32) treatment of these problems led to the conclusion that the ratio of the elastic modulus (E) and the area (A), discussed above,

is a useful design criterion for such assemblies. He designates this ratio as the "effective stiffness coefficient R":

$$R = EA_c / EA_s,$$

where the subscripts *c* and *s* denote crystal compressive stress and axial bolt, or shell, tension section respectively. According to Miller, the allowable range for *R* is between 1 and 25. At the power required for a 25-kilowatt welder, however, creep and/or fatigue considerations will probably prevent *R* from exceeding 2 or 3, which means that a large-diameter unit will be required if the axial tension bolt-type assembly is used. With the tension shell, a ratio of around 1 can be effected in a practical geometry.

Detail drawings were reviewed with personnel of Clevite Corporation (33), who were most cooperative and supplied design data apparently not otherwise available, which has been brought to bear on the problem. In particular, the required static unit clamping stresses were related to the superimposed ultrasonic stresses, while the relation of lateral restraint to the coupling coefficient and the significance of washer thickness were brought into sharper focus.

a. Static pre-stress

Bias stress should insure continuous loading of the ceramic elements. Although some people feel that an optimum bias stress exists for maximum efficiency, Clevite does not recommend more than is necessary.

For an operating *Q* of 10 in the welder transducer-coupling system (which seems reasonable), a maximum alternating stress of 3500 psi (rms) is indicated; i.e., with a peak of 4900 psi, a static bias of 5000-6000 psi should be adequate.

b. Effect of lateral restraint on coupling coefficient

If the ends of the ceramic elements are clamped, and if the wafer is thin, it operates in a laterally clamped longitudinal mode. For this case, the effective coupling coefficient is K_t and not K_{33} ,* which reduces the coupling factor by about 25 percent. To fully realize K_{33} , the length of the crystal should be such that the thickness

* K_t is the transverse coupling coefficient (laterally clamped longitudinal mode).

K_{33} is the coupling coefficient obtained when the crystal is excited in the thickness mode and predominant strain is also in the thickness mode.

resonance is below any lateral resonance. In this type of transducer, this is generally not practical; but if the crystal elements are thick enough to permit relief of the transverse stress, a coupling coefficient intermediate between K_t and K_{33} , but nearer the latter, can be realized. A coupling coefficient near K_{33} can also be achieved by effectively coupling the faces of the ceramic elements to the faces of the metal members if the latter are an integral part of the resonant system, so that the lateral displacement of both the ceramic and metal are equal.

On the basis of the foregoing and the analytical effort associated therewith, the dimensions shown in Table 3 were arrived at for the PZT-4 transducer designs.

Ceramic wafers for the 2.0- and 3.3-kilowatt design were received from Brush Development Company about April 20, and it is expected that the first calorimetric measurements will be made with the 2.0-kilowatt unit during June. Cooling problems and electrical difficulties may be encountered at the outset, but such conditions should be amenable to early resolution. As soon as basic performance data are obtained, the design of the 6.5-kilowatt unit will be finalized and the ceramic elements will be ordered, probably about July 15, 1962.

During this period, information was obtained indicating that a super high-density, pressure-fired lead zirconate titanate ceramic element is available (Gulton Industries). This material is reported to be of more uniform composition and to possess mechanical properties superior to lead zirconate titanate from other sources. Accordingly, some of these elements were ordered and will be tested in the same manner as the original PZT-4 material. The performance of these elements will be compared with that of the original ones, and the better of the two materials will be used in the final 6.5 kilowatt units.

TRANSDUCER DESIGN

Even though the energy required to produce an ultrasonic weld between two pieces of metal has been measured (20) and an equation for estimating the energy necessary to join metals by ultrasonic welding has been developed (21), evaluating the performance of an electromechanical power transducer for an ultrasonic welding machine by incorporating the device in a welder and making welds is impractical. Transducer evaluation based on welder performance is complex, laborious, and likely to be inaccurate unless extreme care is exercised.

Table 3

DESIGN DETAILS FOR 15-KC TENSION-SHELL TRANSDUCERS
(LEAD-ZIRCONATE-TITANATE CERAMIC WASHERS)

Design Power Capacity (kilowatts)	Ceramic Element			Projected Area (inch)	Tension Shell Area (sq. in.)
	Thickness (inch)	ID (inch)	OD (inch)		
2.0	0.500	0.625	2.125	3.240	2.658
3.3	0.375	0.625	2.750	5.633	4.694
6.6*	0.500	0.625	3.883	12.150	9.720

* Four units required for 25-kilowatt welder.

In the course of the Phase I work (34), a practical and direct transducer evaluation method was devised which takes advantage of the metal wave-guide geometry characteristic of welder transducer-coupling systems. The vibratory energy output of the transducer is conducted into an energy absorber, where it is degraded into heat, which is measured calorimetrically.

The device utilized during Phase I has been improved to reduce indeterminate heat losses and to permit rapid measurement of the heat produced by degradation of the vibratory energy. This acoustical calorimeter, assembled largely from available stock laboratory components (see Figure 6), takes power from two sources; first, from the transducer, and second, from a standard a-c power line.

All the energy from both sources is removed from the calorimeter by tap water that flows through a copper tube coil imbedded in the body of the energy absorber. Inlet and outlet water temperatures, as well as water volume, are monitored. In operation, the device is stabilized at some elevated temperature based on a pre-set level of input electrical power from the regular a-c power line feeding resistance wires imbedded in the body of the absorber. When acoustic energy from the transducer is introduced, power from the regular a-c line, which is monitored by a calibrated watt-meter, is decreased to maintain the temperature differential between the input and output water at a constant value. Essentially, the electrical power is decreased by the amount of vibratory power delivered into the absorber unit. Thus, the vibratory power is equal to the observed decrease in a-c electrical power and the over-all energy balance is checked by computing the power delivered into the flowing tap-water heat sink. The energy absorber, enclosed in a tall vacuum chamber at a pressure of about 2 millimeters of mercury, is insulated against thermal losses.

Upon completing the revisions and improvements in the acoustical calorimeter, a standard magnetostrictive nickel stack, consisting of about 300 laminations of "A" nickel 0.008-inch thick (each lamination having a width of 2.25 inch and a length of 5.60 inch) and operating at approximately 15,000 cycles per second, was attached to the calorimeter and evaluated at two levels of input power. These results are summarized in Table 4. Comparison of these conversion efficiencies of 35 percent with that of 21 percent (35) obtained by means of the original, crude, acoustical absorber for the same metal stack, show that the conversion efficiency of the nickel transducer is unquestionably higher than reported previously and that it approximates the figures reported for nickel under good operating conditions. This also implies that the ceramic transducer efficiencies will be well above the 35 percent value found for nickel.

Figure 6: ACOUSTICAL CALORIMETER

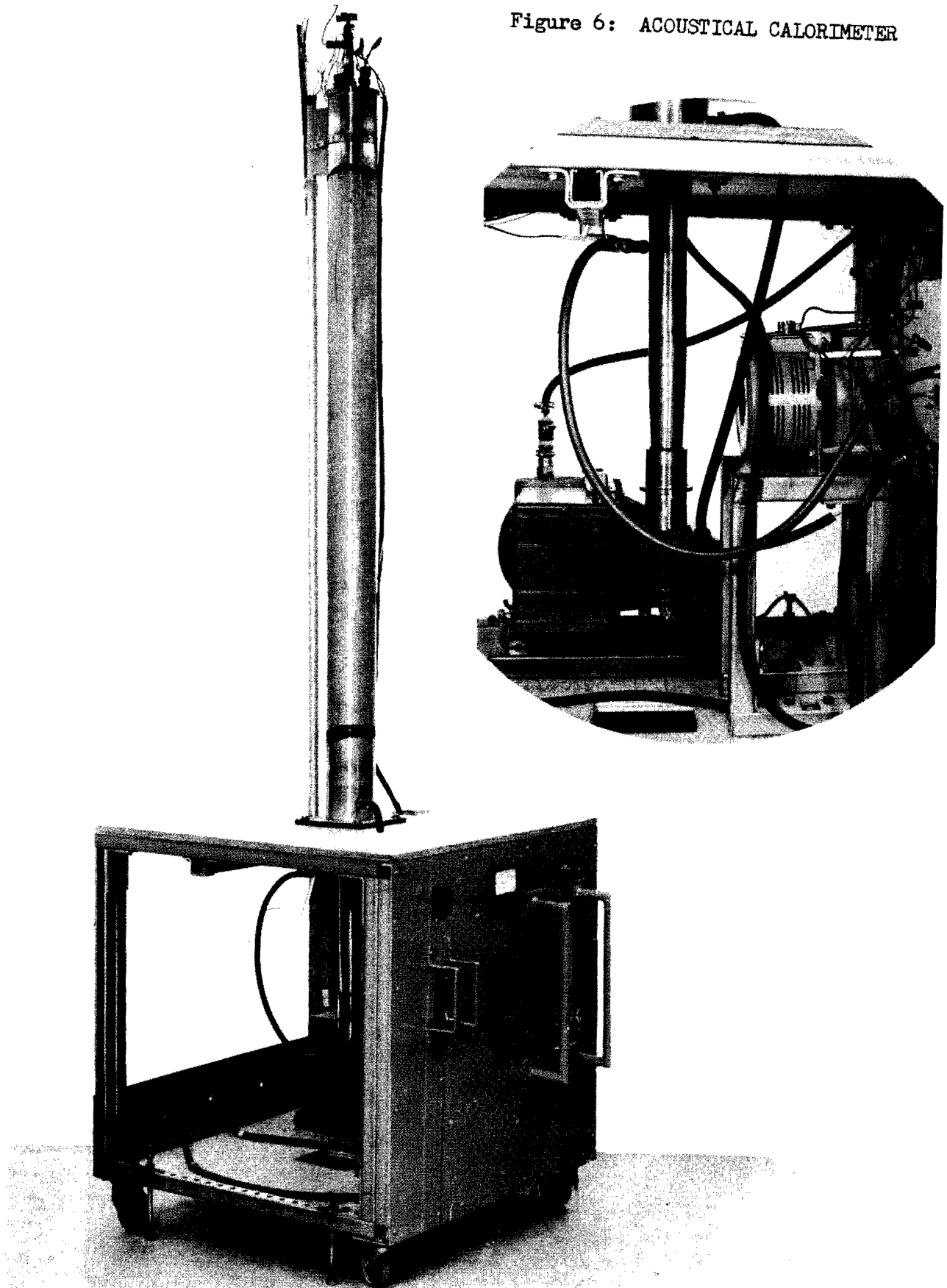


Table 4
NICKEL TRANSDUCER CONVERSION EFFICIENCY BASED ON
CALORIMETRIC MEASUREMENTS

A-C Line Power to Absorber (watts)	H-F Power To Transducer (watts)	Water Flow Rate (cc/sec)	Water Temperature		Conversion Efficiency	
			In (°C)	Out (°C)	Power Rate (a) (percent)	Temperature Differential (b) (percent)
350	0	6.30	23.5	37		
0	1000	6.30	23.5	37	35.0	35.6
575	0	5.26	23.5	50		
0	1650	5.26	23.5	50	34.8	35.3

(a) Computed from Columns 1 and 2.

(b) Derived from Columns 3, 4 and 5.

COUPLERSGEOMETRY

Ultrasonic transducer-coupling systems of the reed-wedge design (36) require that the driving point on the reed be displaced slightly with respect to the peak of its flexural loop. A small flexural component is therefore introduced into the driving end of the coupler that is in contact with the reed. This has not been of much significance in the 4-kilowatt and smaller welding machine systems built to date, but in the 12- to 13-kilowatt systems (two of which make up the 25-kilowatt welder here under development), relieving the flexural stiffness of the driving couplers will be necessary. Moreover, as noted previously, (37), the flexurally soft end of the driving coupler adjacent to the reed should be preferably curved to provide improved work clearance.

During the period covered by this report, an existing 4-kilowatt transducer-coupling system was sculptured to provide a straight, thin section adjacent to the reed connection. Measurements obtained by welding 0.040-inch 2024-T3 aluminum alloy with up to 2-kilowatts input power, when compared with previous data, show that this sculptured coupling system performs at least as well as the standard unsculptured flexurally stiff design.

This sculptured unit will be driven to its maximum power-handling capacity prior to and after bending the flexurally soft section to provide the work clearances and angles necessary in the final unit (37).

FABRICATION

In the Phase I coupler material studies (38), the power-handling efficiency of both aluminum-bronze and beryllium-copper was found to be superior to that of K Monel and of steel alloys. Accordingly, limited work was oriented to resolving the problems of fabricating coupling elements from the aluminum-bronze and beryllium-copper. Initially, beryllium-copper was selected for these fabrication investigations.

Since the quality of beryllium-copper joints, brazed with a recommended alloy (BAg-7 silver braze, Handy and Harmon 560), are affected by both the brazing temperature and time, the effect of these variables was investigated at temperatures of 1250° and 1400°F for time intervals ranging from 1 to 10 minutes. Before brazing, the face of the specimen was divided in half, and one part was given a protective coating to preserve a reference surface. Specimens 1 inch in diameter by 1-1/2 inches long were heated to the brazing temperature, the silver braze was applied, and the beryllium-copper plug was maintained at the brazing temperature for periods of 1, 3, 5, and 10 minutes. Examination of microsections of

the brazed ends indicated an essentially linear relationship between braze penetration depth and time. After 10 minutes, the braze alloy penetrated to a depth of 0.004 inch at 1250°F and 0.008 inch at 1408°F. In addition to these studies, the characteristics of brazed joints between two rods of beryllium copper, and between rods of beryllium-copper and aluminum-bronze were also investigated. Satisfactory joints were obtained in all cases.

It therefore appears that brazing under controlled conditions is satisfactory for joining these materials. However, the rate at which alloying occurs between the braze material and beryllium-copper may well preclude rebrazing such joints.

POWER-FORCE PROGRAMMING

In an ultrasonic welding system, the relative impedance between the terminal element of the system and the weldment material is a significant factor in the delivery of vibratory energy into the weld locale. This impedance changes during the welding interval and is markedly affected by the applied clamping force (20-21). Therefore, pre-set programming of the clamping force applied during the weld interval will compensate, at least in part, for variations in impedance during that interval.

Power Programming, which pre-programs the power delivered during an ultrasonic weld interval, is a further method for controlling the weld quality and for reducing the total energy necessary to generate an ultrasonic bond.

The power-force programming (PFP) system was reviewed from electrical, electronic and mechanical standpoints. The original time-base control circuit was modified to incorporate commercially available transistorized time-delay circuitry. With the transistorized circuit, the response time is approximately 0.0005 second and, within the range of 0 to 1.0 second, the reproducibility of the time setting is 0.2 percent. The reset time is 0.050 second.

The power-force programming circuitry includes a control panel, which provides a matrix system of ten increments each, for adjusting the power and force by increments which are 10 percent of the full power or force value. The addition of a percent time-base increment for any given weld time interval then yields a 10 square matrix control system.

Auxiliary relays of the air-reed type were selected to provide multiple-event control at any time increment. These relays have a response time of 0.007 to 0.0017 second, and permit control of two or more events. Additional relays can be added, as needed, to control tangent circuits.

The variations in power will be controlled by adjusting the oscillator signal level of an electronic generator, or by switching resistive loads into, or out of, the transmission line for a motor-alternator power source.

Elements for three stages of the time-base control circuit were procured and evaluated. On the basis of this information, the remaining elements were ordered. The associated force-control components, including a precision hydraulic feed-back control system, which will respond to the programming circuitry, have been ordered and are scheduled for delivery in late May or early June.

When assembled, this unit will be attached to an existing ultrasonic spot-welding machine for evaluation.

TIME-BASE CONTROL ELEMENT

A portion of the time-base control circuitry for the power-force programming system was evaluated by applying the relay output to an oscilloscope and measuring the response of a single relay unit and the time delay between successive relay steps. The time delay was 0.002 second, which meets the design requirements for these basic components.

The over-all time-base response and control characteristics of this unit were then determined at three power levels, which have no significance per se except to provide time-base markers. The unit was attached to a standard 2-kilowatt ultrasonic welder. Three levels of power were applied, and the delay between the time-base control signal to the power source and the stress wave traversing the coupler enroute to the weld zone was recorded on strip charts. The stress-wave monitor was placed on the coupler in the vicinity of the coupling-reed joint. Note that the ordinate of these records is of no significance except to provide time-base markers, as stated above.

The oscillogram of Figure 7A was made at an oscilloscope trace speed of 10 milliseconds per centimeter. The two strip-chart records, shown in Figures 7B and 7C, were made at weld pulse intervals of 1.0 and 0.6 second, respectively. The lower recording of Figures 7B and 7C represent the electrical analogue of the stress wave at a point near the coupler-reed joint. The relative time delay between the upper and lower oscillograms of Figures 7B and 7C represent the total accumulated time delay between the initiation of electrical power delivery at the power source and the arrival of the resulting ultrasonic power in the weld zone. As indicated by Figure 7, the time delay is within the design specifications. Thus the basic circuitry for the time-base control element is satisfactory.

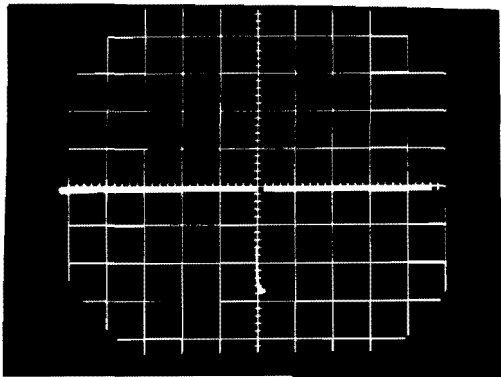
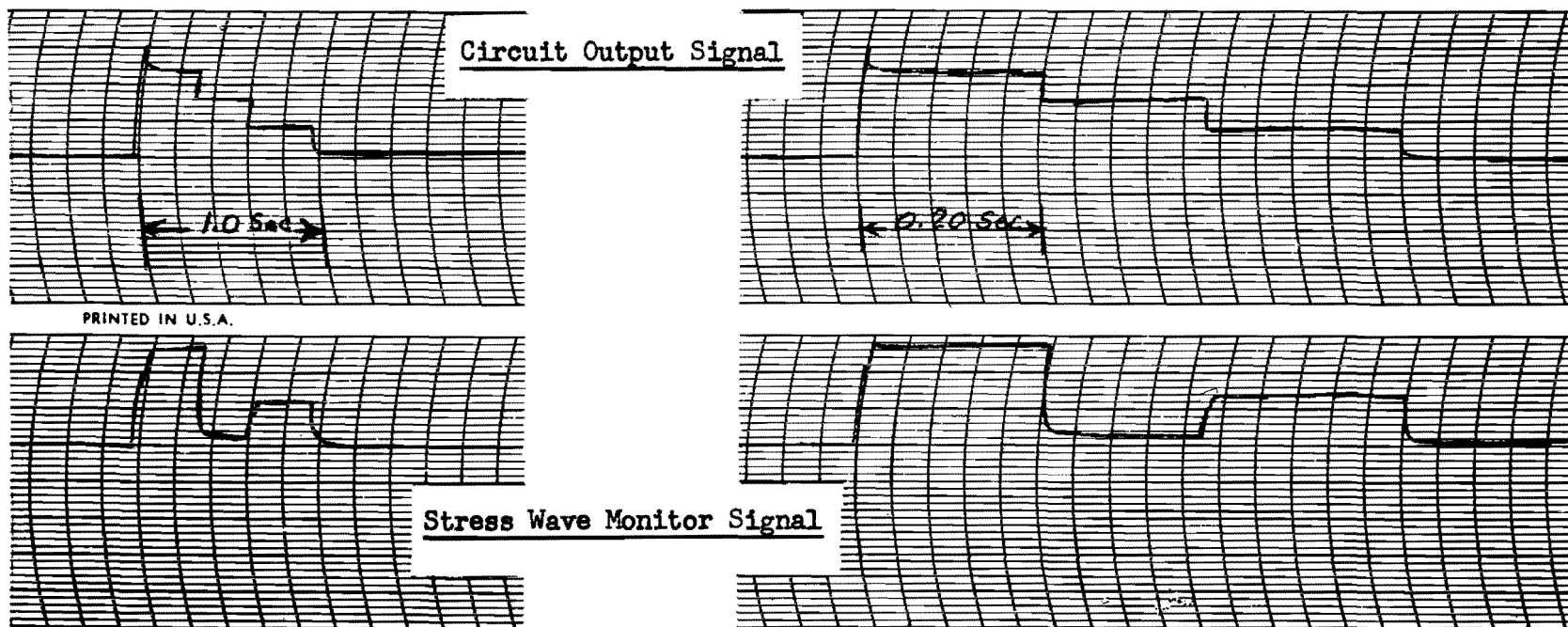


Figure 7

TIME-BASE CONTROL CIRCUIT RESPONSE

A. Time-Delay Oscillogram
(Trace Speed: 10 ms/cm)



B. 1.0-second Weld Pulse Interval

C. 0.6-second Weld Pulse Interval

POWER SOURCE

The effort of Phase I was not concerned with the power source for driving the transducers, since the selection, design, and construction of a suitable power source was considered an engineering rather than a development problem.

During the past few years, electronic power sources in the range of about 5 watts to 8 kilowatts have been designed and constructed. Motor-alternator sets in the range of 2- to 7.5-kilowatts have been appropriately modified and used to drive ultrasonic welding machines in our laboratories. Machines capable of providing 50 or more kilowatts can be supplied. Furthermore, solid-state semi-conductor devices have been designed and constructed; the projected designs for such equipment currently extends up to 50 kilowatts.

Consideration has been given to the merits of each type of power source for high-powered ultrasonic welding equipment. An ultrasonic transducer-coupling system operates effectively only at or near its resonant frequency, and frequency stability is therefore important. For spot-type welding, the voltage and current buildup from zero to full power must be achieved in a very short time, because best welds are produced at relatively short weld intervals (considerably less than 1 second).

MOTOR ALTERNATORS

A 7.5-kilowatt motor alternator with precision adjustable drive is in continuous use on commercial ultrasonic welding equipment. Performance of this unit continues to equal or exceed the tentative specifications previously established. The output frequency, a nominal 15,000 cycles per second, is being maintained at ± 8 cycles. Adjustment of the frequency precisely to $\pm 3-5$ cycles per second is straightforward; thus adequate stability of the critical frequency control is indicated. Frequency output values are given in Table 5 for the 7.5-kilowatt motor alternator operating over a 6-hour day with the frequency output set at 14,924 cycles per second. These values were recorded over a period of approximately 1 hour on separate days.

The satisfactory performance of the 7.5-kilowatt motor alternator demonstrates the practicability of a motor-alternator power source for ultrasonic spot-type welding equipment.

SWITCHING

In the electrical industry, power at high levels is switched routinely by means of magnetic contactors which are remote-controlled. The response characteristics of the switching device required to handle

Table 5

FREQUENCY OUTPUT DATA FOR 7.5-KILOWATT MOTOR ALTERNATOR

(Frequency Output Setting: 14,924 cycles per second)

Test Day: 6 hours

Test Day	Measured Frequency (cycles/second)			Number of Measurements	Frequency Value	
					Average (X) (cycles/second)	Standard Deviation(s)
1	14,921	14,924	14,922	13	14,922	3
	14,923	14,926	14,925			
	14,924	14,923	14,922			
	14,918	14,919	14,916			
	14,923					
2	14,924	14,924	14,927	20	14,926	2
	14,928	14,928	14,926			
	14,924	14,924	14,925			
	14,927	14,925	14,926			
	14,927	14,926	14,925			
	14,928	14,926	14,927			
	14,928					
	14,928	14,924				

25 kilowatts of 15-kc electrical power from a motor-alternator source at the envisioned welding intervals, however, may be critical. With the anticipated welding repetition rate, accurate switch control varying from 0.01 to 1.0 second will be necessary.

On the basis of preliminary measurements, the switching performance of parallel banks of high-current magnetic contactors equipped with arc-suppression coils was satisfactory, but the service life of these units may be inadequate for our purposes, and work is underway to evaluate high-current solid-state switches. Such devices promise trouble-free performance without the attendant concern of arc-over and the time lag associated with the opening and closing times of contactor-type controls.

Solid-state switching devices that meet the following requirements:

- a. high transient and repetitive peak inverse voltage,
- b. 35 amperes of high-frequency (15-kc) current,
- c. time to recover forward blocking state after forward current passage,
- d. gate-timing synchronization requirements, and
- e. other special circuitry requirements, such as transient suppression devices

were selected on the basis of information and advice supplied by General Electric specialists of the Semi-Conductor Division, Auburn, New York. At that time, several C55E (General Electric) type units were acquired.

These solid-state switching devices were tested at an intermediate power level of 3 kilowatts. Neglecting the time delay inherent in the associated circuitry, a response time of the order of 8 to 12 microseconds was obtained. Thus, multiple solid-state units are promising as switching devices for motor-alternator power outputs. Subsequent tests will be made up to the full power capacity of the 7.5-kilowatt unit. These solid-state devices can also be used for switching partial resistive loads into the line to permit power programming with the alternator power sources. Solid-state switching units will probably be used with the power source in the final design of the 25-kilowatt ultrasonic welding machine.

STRUCTURAL DETAILS

Design of the welding-machine framework was initiated during this period in accordance with the tentative requirements outlined previously (2). This structure will provide: a working throat depth of 36 inches or greater, a total head movement of 4 inches or more when mounted on heavy-duty way slides, and a rigid framework to minimize welding tip displacements during welding. The machine will be capable of applying a clamping force of 4000 pounds to the weldment. The preliminary layout of the machine is shown in Figure 14 of ASD Interim Report 7-888(II).

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